Title

Correlating Reaction Time and Nausea Measures with Traditional Measures of Cybersickness

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Abstract

We provoked cybersickness in participants by immersing them in one of two virtual roller coaster rides using a head-mounted display. As simulation technology is often used in training, our main intention was to examine the effect of the experience on their cognitive function. Participant reaction times before and after the experience were measured by averaging their response time to a visual stimulus over a number of trials. We measured a significant reduction in response time before and after the virtual experience. We also examined the changing state of nausea experienced by participants using some simple nausea measures. These included a repeated nausea rating recorded by participants at two-minute intervals. At the completion of the experience, we averaged these ratings to create a standard nausea score. As participants could decide to stop the experience at any time, we also recorded the voluntary duration of the experience. We correlated our measures with two traditional simulator sickness measures, namely the Motion Sickness Susceptibility Questionnaire (MSSQ) and Motion Sickness Assessment Questionnaire (MSAQ). The standard nausea score provided a simple measure of nausea that could be collected at regular intervals with minimal interference to the immersive experience, and was significantly correlated with both the MSSQ and MSAQ scores.

Key Words

Cybersickness, Nausea, Reaction Time, Susceptibility, Assessment

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1 Introduction

The technology associated with virtual reality [1] has been under constant development since Ivan Sutherland first described many of the concepts surrounding his Ultimate Display [2,3]. Over the intervening years, much progress has been made in developing the various technologies required for generating seamless, natural interaction in virtual worlds [4] and to meet some of the visionary goals described for Virtual Reality [5]. A broad application of this technology remains the domain of training and education. However, there has been a recent growth in demand for affordable immersive environments, particularly head-mounted displays (HMDs). For example, cost effective devices such as the Oculus Rift HMD are evolving to meet a growing consumer demand [6]. Affordable display technologies associated with PlayStation VR [7], HTC Vive [8], and Google [9] have also emerged to try and meet the expected demand for immersive game interfaces, and for social interaction with applications such as Facebook [10].

However, one problem still experienced in immersive simulations is the uncomfortable side effects associated with conditions such as cybersickness [1]. Previous research has shown that participants can experience a range of unpleasant physical responses when subject to virtual environments [11,12,13]. These generally minor, short-term health risks [14] remain a potential issue for the broader adoption of these technologies. While for most people the effects are minor, some estimates for the percentage of the population affected during exposure are as high as 60-80% [11,15].

Typical symptoms of cybersickness include nausea, eyestrain and dizziness [16]. Motion sickness and simulator sickness share many symptoms with cybersickness. This includes apathy, sleepiness, disorientation, fatigue, vomiting, and general discomfort, which are typical of the symptoms trainees may experience in simulators [16]. Furthermore, post-training effects can impact on individuals, with effects such as drowsiness or postural instability occurring immediately after training or even many hours later [17]. In this study we focus on symptoms of nausea and changes in participant reaction time.

Symptoms are known to vary greatly between individuals, and depend on the technologies being used, the design of the environment, and the tasks users are performing in the environment [17]. There is an evident relationship between the symptoms of motion sickness, simulator sickness and cybersickness [12]. Although, in each case these symptoms are induced by exposure to slightly different situations, and different clusters of symptoms seem to differentiate the three conditions [12]. Motion sickness is the unpleasant feeling, accompanied by nausea, dizziness, and vomiting, that may occur when people travel in moving vehicles. Astronauts can also experience a related form of motion sickness; called ‘space adaptation syndrome’ that occurs in exposure to zero gravity conditions [18]. Simulator sickness occurs in simulators with moving platforms when discrepancies between the perceived and actual motion occur [19]. Cybersickness affects stationary users who experience the sensation of moving in the virtual scene [18]. In our study, we provoke this condition by immersing stationary users in a virtual roller coaster ride using a HMD.

Both subjective [11,12,18,20-29] and objective [13,30-36] approaches have been applied to try and understand the multiple factors that impact on these conditions, the types of symptoms, as well as the susceptibility of individuals to the various symptoms. Historically, one of the earliest survey instruments for assessing motion sickness [37] was known as the Pensacola Motion Sickness Questionnaire [38]. It was based on 27 previously identified issues [22]. This early work led to the development of the Pensacola Diagnostic Index [28], calculated by summing an individual's ratings on various scales related to the symptoms of dizziness, headache, warmth, sweating, drowsiness, salivation, and nausea.

As simulation technology developed, the Pensacola Motion Sickness Questionnaire was modified several times until, after a major study analyzing the symptoms relevant to simulator sickness, an alternative 16-item Simulator Sickness Questionnaire (SSQ) [23,25,26] was proposed. These 16 symptoms were found to cluster into three categories; oculomotor, disorientation, and nausea. The oculomotor cluster included eyestrain, difficulty focusing, blurred vision, and headache. The disorientation cluster symptom included dizziness and vertigo. The nausea cluster included stomach awareness, increased salivation, and burping. While correlated with the previous Pensacola Motion Sickness Questionnaire, this new questionnaire also allowed the identification of multivariate measures related to the oculomotor, disorientation, and nausea dimensions.

One dimension of cybersickness that was not directly assessed by the Simulator Sickness Questionnaire was the sopite syndrome [38]. This dimension includes symptoms such as drowsiness, yawning, and disengagement from the environment [39]. To address this issue, a further multivariate questionnaire was developed to measure the symptoms associated with the four subscales of gastrointestinal, central, peripheral, and these sopite-related symptoms [20] (See Table 1). Because the Motion Sickness Assessment Questionnaire (MSAQ) [20] is one of the more commonly used multivariate questionnaires for recording cybersickness symptoms, we have also incorporated this into our own study.

In terms of gauging individual susceptibility to symptoms, the Motion Sickness Susceptibility Questionnaire (MSSQ) is one of the traditional approaches [20]. It relates a user's experience with motion sickness, both as a child and adult, to predict the likelihood of a person also suffering from cybersickness [18]. The original MSSQ [26] is the most widely used and validated approach to assessing an individual's susceptibility to such conditions [18]. This original MSSQ was updated in 1998 to simplify the rating and scoring mechanisms [18]. This newer validated questionnaire captures the individual's travel experiences and their relation to any nausea or vomiting. It records experiences both prior to the age of 12, and in the individual's previous 10 years in a variety of vehicles such as cars, buses, trains, aircraft, and boats, as well as fairground and playground rides. A susceptibility rating is calculated on the basis of quantified Likert rankings regarding the severity of experiences and the frequency of occurrences. Because of the prominent historical use of this susceptibility questionnaire, we decided to include it in our own study.

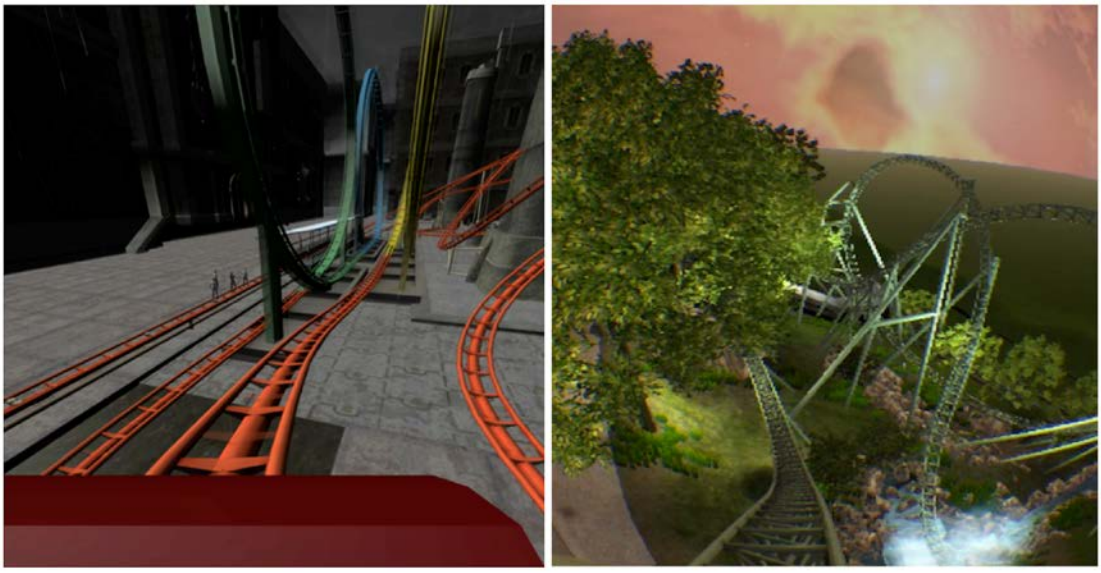

Figure 1: Typical frames from the ParrotCoaster (left) and Helix coaster (right) used in the study.

We are particularly interested in studying the onset of nausea in relation to cybersickness caused by immersive experiences in HMDs. To avoid too great an impact on the immersion of the experience, we are trying to gather nausea ratings that only require minimal feedback from participants. In this experiment we consider two simple measures; the duration of voluntary exposure (0-14 minutes) and a standard nausea score (0-10) collected over the period of the virtual experience. The standard nausea score is intended to capture the amount of nausea the participant would experience over the full of the ride. It is an average of the participants 7 nausea ratings taken at each 2-minute period of the ride. Where a participant has decided to leave the ride early, it uses the participants' final nausea rating for the calculation. Our intention is to correlate these simple nausea measures with more traditional and well-validated simulator sickness instruments, namely the revised MSSQ [18] and the MSAQ [20]. Of particular interest is any correlation between the MSAQ-Gastrointestinal subscale and our nausea measures.

As these types of virtual experiences are often proposed for training situations, we also wished to measure any affect cybersickness might have on cognitive function. In this study we measure changes in user reaction time after exposure to the virtual experience. Again we wanted to try and correlate this measure with the MSSQ [18] and MSAQ [20] scores. In this case we were particularly interested in any correlation between the MSAQ-Central subscale and any changes detected in participant reaction time.

In summary there are a number of questions we addressed in this study:

1. Are there any indications of impaired reaction times [40] that result from cybersickness, and how does this measure correlate with the MSAQ scores [20]?
2. Do our nausea measures, voluntary exposure time and standard nausea score, correlate with the cybersickness symptoms measured with the traditional MSAQ scores [20]?

3. How well does the MSSQ score [18] correlate with our simple nausea measures and changes in participant reaction time?

2 Method

An experiment was conducted on 24 participants aged from 18 to 32, with an average age of 22.5 years (SD=3.5). Overall, 79.2% (19/24) of participants were male and 20.8% (5/24) were female. We also collected information about participant exposure to virtual environments in the form of video games. Twenty-five percent (6/24) of participants played 0 to 5 hours of video games per week, 25% (6/24) played 5 to 10 hours of games per week, while 50% (12/24) played more than 10 hours of games per week. The participants were mostly undergraduate students studying Information Technology. Participants were only included if they had normal vision and vestibular function, and were not suffering from symptoms of cold or flu. Participants were also excluded if they were pregnant or were known to suffer from conditions that might be aggravated by wearing an immersive HMD, such as vertigo, claustrophobia, or epilepsy.

Approval for the study was obtained from the Newcastle University Human Research Ethics Committee (Approval number: H-2014-0266). The Ethics Consent Form explained that the aim of the experiment was to investigate nausea associated with a roller coaster ride simulated in a HMD, and advised participants that they were free to withdraw from the study at any time.

To account for potential stimulus specific effects, two different virtual roller coasters were used in the experiment. The 24 participants were randomly allocated into one of two groups of 12 to experience one of two virtual roller coaster rides using the Oculus Rift DK1 running firmware version 0.18, with default (A) lenses. The first group (9 males and 3 females) experienced the ParrotCoaster virtual roller coaster [41], and the second group (10 males and 2 females) experienced the Helix virtual roller coaster [42]. Both experiences were intentionally selected for their potential to provoke cybersickness in stationary users by providing immersive sensations of motion.

The ParrotCoaster [41] is implemented using a simple, cartoon-like graphics style and continually loops around a circuit that has an individual duration of 1.44 minutes. By contrast, the Helix roller coaster uses higher fidelity, and more realistic, graphics. Fidelity has previous been highlighted as a factor that can increase simulator sickness [43]. The Helix coaster ride had duration of 1.30 minutes and required the user to restart the loop on completion. The use of two roller coasters provided a broader range of immersive experience for participants. The Helix roller coaster has previously been shown to produce significantly greater nausea symptoms than the ParrotCoaster [44].

Prior to experiencing the virtual roller coaster, participants completed Golding's revised MSSQ [18]. Subjects were also asked to rate their nausea level on a subjective scale between "0–no nausea/discomfort" to "10-very nauseous (feel like vomiting)". All participants provided an initial ranking of no nausea (0). Participants then completed a single choice Deary-Liewald Reaction Time Task [40]. This task involves participants watching a white box in the middle of a blue screen, and reacting by pressing the space key when a black cross appears. The reaction time task

was pre-configured for 40 trials with a response range of 100ms to 1500ms and a randomized inter-stimulus interval of between 1000ms and 5000ms. These trials took in the order of 5 minutes to complete. At the conclusion of the task, the mean response time of the 40 trials was calculated as a measure of cognitive function before immersion.

Following the reaction time pre-test, the participant was fitted with the Oculus Rift DK1 and instructed to adjust the device for comfort. The participant then viewed a static stereoscopic image for five minutes to allow the user to adjust to wearing the HMD. Participants were told that the virtual roller coaster would last for 14 minutes. They were reminded that they could stop the experiment at any time and remove the HMD if they felt too nauseous to continue. At two-minute intervals participants verbally rated their nausea level on the same subjective scale between 0 (No nausea) and 10 (I'm ready to vomit). Participants who stopped early had their stop time recorded and were asked to provide a final nausea rating.

During the ride, participants were free to look around as they wished. Both roller coasters provided a fully immersive, 360-degree view of the roller coaster ride that was mapped to their head movement. At the completion of the virtual experience, participants provided a final nausea rating before removing the Oculus Rift. Immediately after the Oculus Rift was removed, the single choice Deary-Liewald Reaction Time Task [40] was performed once more. Thus this task was completed within 5 minutes of completing the ride. The configuration of this task was identical to the pre-experiment task. Again, the 40 post-experiment reaction time trials were averaged to calculate an average response time. Finally, participants reported on their symptoms using the standard MSAQ [20].

3 Results

3.1 Coaster Differences

The various nausea ratings recorded for the 24 participants are shown in Table 1. For the ParrotCoaster, 16.7% (2/12) of participants were not able to complete the 14 minutes of ride time due to nausea. This compares with Helix, where 66.7% (8/12) of participants stopped prematurely. We compared the average ride time in minutes for participants on both coasters using an independent samples t-test. Assuming equal variance, the average ride time, in minutes, was significantly different for the ParrotCoaster (M=12.7, SD=3.1) and the Helix coaster (M=8.17, SD=4.7); $t(22)=2.77$, $p^* = 0.011$. We also compared the standard nausea score for participants on both roller coasters using an independent samples t-test. Again, there was a significant difference in this subjective rating for ParrotCoaster (M = 2.70, SD = 2.45) and Helix (M = 4.91, SD = 2.28) conditions; $t(166) = 1.97$, $p = .000^*$. We checked other measures and the only other significance difference we found was in the MSAQ-Peripheral score for ParrotCoaster (M = 24.69, SD = 14.68) and Helix (M = 42.3, SD = 24) conditions; $t(22) = 2.07$, $p = .041^*$.

The Helix coaster is more provocative than the ParrotCoaster, with participants tending to develop more severe nausea symptoms more rapidly on the Helix coaster (see Figure 2). The parametric and non-parametric correlations for the ParrotCoaster (n=12) and the Helix coaster are provided (see Table 2, 3). However, as the larger,

combined data set (n=24) provides a broader range of onset times and symptom severity, we selected to use this for further correlation analysis (see Table 4) and discussion.

Table 1: Participant's subjective nausea ratings after every 2 minutes. The rows are sorted by standard nausea score and ride duration so participants that experience the greatest nausea are found at the bottom of the table.

Nausea Rating (0-10) (Every 2 minutes)								Voluntary ride time (0-14 minutes)	Standard Nausea Score (0-10)	Coaster
0	**2**	**4**	**6**	**8**	**10**	**12**	**14**			
0	0	1	1	1	1	1	1	14	0.86	Parrot
0	0.5	0.5	2	0.5	0	2	3	14	1.21	Parrot
0	0	0	1	1	2	2	3	14	1.29	Parrot
0	1	3	2	1	1	1	1	14	1.43	Parrot
0	0	1	1	2	4	2	2	14	1.71	Parrot
0	2	1	1	1	2	2	3	14	1.71	Parrot
0	0	1	2.5	2	2	3	2	14	1.79	Parrot
0	1	1	1	2	2	3	3	14	1.86	Parrot
0	1	1	1	1.5	3	3	4	14	2.07	*Helix*
0	2	2	3	3	3	3	4	14	2.86	Parrot
0	0	1	3	4	4	4	4.5	14	2.93	*Helix*
0	2	2	3	2	3	4	6	14	3.14	*Helix*
0	3	3	4	5	4	5	4	14	4.00	*Helix*
0	1	2	4	4	6	7	7	14	4.43	Parrot
0	0	1	4.5	6	6	6	6	8	4.21	*Helix*
0	1.5	3	5	6.5	6.5	6.5	6.5	8	5.07	*Helix*
0	1	3	5	6	6	6	6	7	4.71	*Helix*
0	1	4	5	7	7	7	7	7	5.43	*Helix*
0	5	6	7	10	10	10	10	6.5	8.29	Parrot
0	1	4	6	6	6	6	6	6.0	5.00	Parrot
0	3	5	7	7	7	7	7	4.5	6.14	*Helix*
0	5.5	7	7	7	7	7	7	3	6.79	*Helix*
0	3	7	7	7	7	7	7	2.5	6.43	*Helix*
0	8	8	8	8	8	8	8	2	8.00	*Helix*

3.2 Descriptive Measures

The duration of voluntary exposure recorded how long the participants could ride before they needed to stop due to feelings of nausea (M=10.44, SD=4.54). Overall, 42% (10/24) of participants were not able to complete the 14 minutes of ride time due to nausea. As a measure of overall nausea sensation, we calculated the standard nausea score using the participant nausea ratings made at two-minute intervals (see Table 1). This standard score was calculated by taking the average of the seven user ratings made with the same subjective rating scale (M = 3.81, SD = 2.24). For participants who experienced 14 minutes of ride time, this was the average of the seven nausea ratings made at each two-minute interval in the experiment. For the 10 participants who finished early, we simply used their last nausea rating for any of the two-minute intervals they had not remained on the ride.

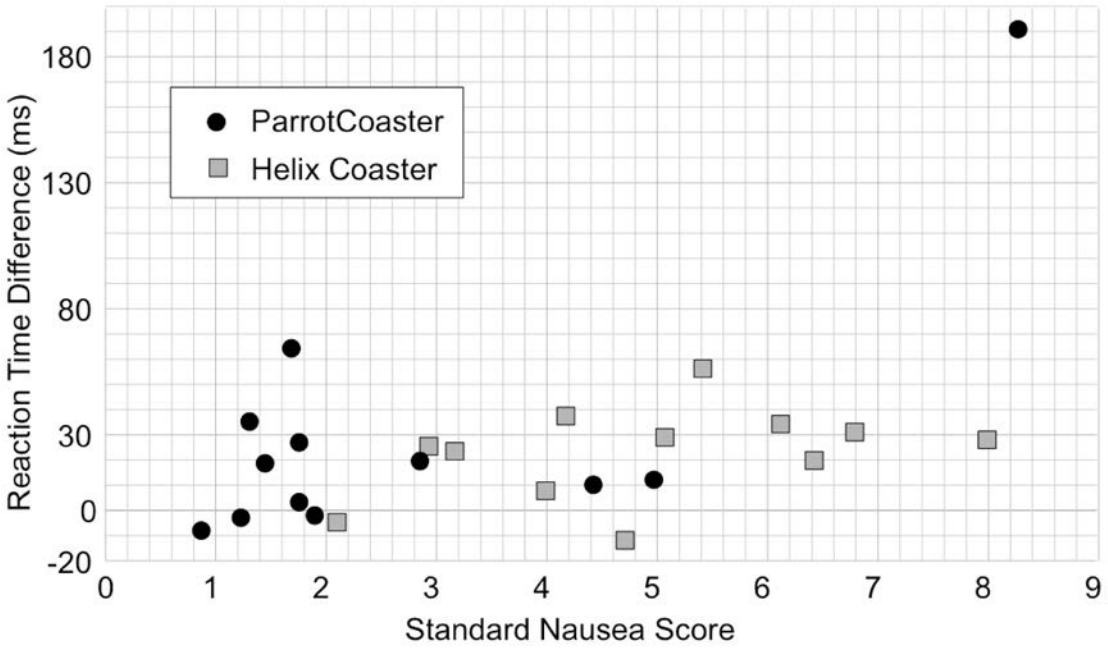

Figure 2: Relationship between the change in participant reaction time and their standard nausea score.

Each participant completed 40 trials of the single choice Deary-Liewald Reaction Time Task [40], both before and after experiencing the virtual roller coaster rides. For each participant, we calculated the difference between the mean of their 40 pre-experience reaction time trials and their 40 post-experience reaction time trials (see Figure 2). Overall, there was an increase in the mean and variance of reaction time from pre-test (M=422.90, SD=18.75) to post-test (M=449.14, SD=48.06). This represents an average increase of 26.25 ms (SD=39.92) to reaction time. Both a parametric t-test and a nonparametric test were performed on the mean pre and post reaction times since it was unclear if the distributions were normally distributed. Both these tests indicated the increase in mean reaction time was significant. The result for the parametric t-test was $t(24) = 3.22$, $p = .004$ and the result for the nonparametric test was $p < .0001$.

In terms of susceptibility, the traditional MSSQ score (M= 38.43, SD=32.42) was calculated in two parts corresponding to motion sickness experiences recalled from childhood (MSSQ-A) (M= 22.39, SD=19.87), and more recent adult experiences (MSSQ-B) (M= 16.03, SD=14.92). These measures were calculated using the standard procedure for the MSSQ survey instrument (Golding, 1998).

At the completion of the experience, the traditional motion assessment survey was used to calculate an overall MSAQ-Total (M=31.93, SD=13.87). Scores for the four MSAQ sub-scales, the MSAQ-Gastrointestinal (M=39.93, SD=23.46), MSAQ-Central (M=24.16, SD=11.32), MSAQ-Peripheral (M=33.48, SD=21.43) and MSAQ-Sopite (M=23.60, SD=12.70) were also calculated from the survey responses.

Table 2. Pearson (r) and Spearman (r_s) Correlation Coefficients for Parrot Coaster measures (n=12) (2-tailed significance ** p < 0.01; *p < 0.05)

		Standard Nausea Score	Reaction Time Difference	MSSQ	MSAQ Total	MSAQ - Gastrointestinal	MSAQ - Central	MSAQ - Peripheral	MSAQ - Sopite
Voluntary Duration	r r_s	-.833** -.641*	-.591* -.290	-.482 -.442	-.847** -.644*	-.774** -.575	-.820** -.643*	-.606* -.399	-.874** -.654*
Standard Nausea Score	r r_s		.748** .350	.584* .256	.947** .656*	.950** .797**	.855** 0.498	.718** .414	.817** .514
Reaction Time Difference	r r_s			.353 .091	.814** .408	.642* .374	.685* .316	.776** -.117	.758** .747**
MSSQ	r r_s				.638* .677*	.644* .443	.693* .738**	.472 .163	.415 .310
MSAQ Total	r r_s					.911** .785**	.944** .896**	.767** .096	.906** .777**
MSAQ - Gastrointestinal	r r_s						.804** .477	.549 .078	.779** .678*
MSAQ – Central	r r_s							.702* .249	.874** .630*
MSAQ – Peripheral	r r_s								.569 -.159

Table 3. Pearson (r) and Spearman (r_s) Correlation Coefficients for Helix Coaster measures (n=12) (2-tailed significance ** p < 0.01; *p < 0.05)

		Standard Nausea Score	Reaction Time Difference	MSSQ	MSAQ Total	MSAQ - Gastrointestinal	MSAQ - Central	MSAQ - Peripheral	MSAQ - Sopite
Voluntary Duration	r r_s	-.938** -.957**	-.347 -.307	-.485 -.660*	-.358 -.550	-.770** -.780**	-.168 -.170	.155 0.054	.188 0.182
Standard Nausea Score	r r_s		.408 .420	.618* .751**	.332 .476	.780** .767**	.101 0.60	-.152 -.144	-.208 -.191
Reaction Time Difference	r r_s			.565 .477	.140 .028	.354 .196	.052 -.004	-.254 -.284	-.033 -.014
MSSQ	r r_s				.501 .474	.608* .596*	.308 .185	.022 -.070	.304 .069
MSAQ Total	r r_s					.755** .802**	.864** .816**	.563 .491	.561 .495
MSAQ - Gastrointestinal	r r_s						.511 .432	.120 .202	.077 .152
MSAQ – Central	r r_s							.360 .297	.667* .696*
MSAQ – Peripheral	r r_s								.220 .193

Table 4. Pearson (r) and Spearman (r_s) Correlation Coefficients for Combined measures (n=24) (2-tailed significance ** p < 0.01; *p < 0.05)

		Standard Nausea Score	Reaction Time Difference	MSSQ	MSAQ Total	MSAQ - Gastrointestinal	MSAQ - Central	MSAQ - Peripheral	MSAQ - Sopite
Voluntary Duration	r r_s	-.884** -.863**	-.289 -.392	-.161 -.364	-.622** -.650**	-.795** -.750**	-.482* -.467*	-.260 -.340	-.295 -.288
Standard Nausea Score	r r_s		.497* .420*	.316 .362	.750** .745**	.870** .879**	.564** .525**	.377 .420*	.430* .408*
Reaction Time Difference	r r_s			.384 .205	.541** .333	.418* .312	0.406* .158	.241 .045	.576** .383
MSSQ	r r_s				.402 .487*	.385 .447*	.396 .444*	.093 .066	.342 .241
MSAQ Total	r r_s					.848** .857**	.908** .873**	.673** .507*	.750** .714**
MSAQ - Gastrointestinal	r r_s						.679** .624**	.376 .340	.453* .532**
MSAQ – Central	r r_s							.535** .384	.755** .697**
MSAQ – Peripheral	r r_s								.349 .134

3.3 Correlations

Pairwise Pearson product-moment correlation coefficients were computed to assess the relationship between our two simple nausea variables: the duration of voluntary exposure and, the standard nausea score (see Table 4). Due to the sample size, we also checked for nonparametric correlations using Spearman's coefficient (see Table 4). With both the Pearson and Spearman calculations, we found significant negative correlations between the standard nausea rating and voluntary duration.

Next we considered how the difference in the participant's pre and post reaction times correlated with the two nausea variables (see Table 4). Again Pearson product-moment correlation coefficients and Spearman correlations were computed to assess the relationship between each pair of variables. For both the parametric and non-parametric approaches, there was a significant correlation between the reaction time difference and standard nausea score (see Figure 2). The Pearson correlations between the reaction time difference and the MSAQ-Total, and all of its subscales except the MSAQ-Peripheral, were significant. However, these correlations could not be confirmed using the non-parametric approach.

Pearson and Spearman coefficients were then computed to assess the relationship between the results for the MSAQ Total and its four subscales, MSAQ-Gastrointestinal, MSAQ-Central, MSAQ-Peripheral, and MSAQ-Sopite (see Table 4). Both the parametric and non-parametric approaches confirmed correlations between the MSAQ-Total and all four of the MSAQ subscales. Similarly, the MSAQ-Central score was significantly correlated with the MSAQ-Gastrointestinal using both approaches. Likewise, we found significant correlations between the MSAQ-Sopite and the MSAQ-Gastrointestinal as well as the MSAQ-Central score.

We then considered our two nausea variables and used the 24 samples to calculate Pearson and Spearman correlations for the MSAQ-Total, as well as the four MSAQ subscales (see Table 4). For both the parametric and non-parametric approaches, the MSAQ, MSAQ-Gastrointestinal and MSAQ-Central subscales were negatively correlated with the voluntary duration and positively correlated with the standard nausea score. Both the Pearson and Spearman calculations also indicated significant positive correlations between the MSAQ-Sopite and the standard nausea score. The non-parametric correlation between the standard nausea score and the MSAQ-Peripheral were also significant.

Finally to gauge how well our nausea results were predicted by the MSSQ, we calculated Pearson product-moment correlation coefficients and Spearman's correlation coefficients between our two simple nausea variables, and the overall MSSQ score (see Table 4). No significant negative correlation was found between the voluntary duration and the MSSQ or the standard nausea score and the MSSQ. We also examined the relationship between the MSSQ score and the symptoms measured by the MSAQ-Total and its four subscales. None of the parametric calculations indicated any significant correlations between the MSSQ and the MSAQ-Total or the four MSAQ subscales. However, the non-parametric calculations found significant correlations between the MSSQ and the MSAQ-Total, MSAQ-Gastrointestinal and MSAQ-Central.

4 Discussion

The first issue we examined in the study was any indications of impaired reaction time [40] that might result from cybersickness, and how this reaction time measure might correlate with the various nausea measures in the study. We measured changes in participants mean reaction time using forty trials of a single choice Deary-Liewald Reaction Time Task [40] and found a significant difference between pre-test and post-test results. This suggests that participants experienced a drop in cognitive performance as a result of cybersickness. This reaction time change was significantly correlated with the standard nausea score. Significant Pearson correlations were also found between these changes in reaction time and the MSAQ-Total, the MSAQ-Gastrointestinal, and the MSAQ-Sopite subscales. The MSAQ-Central dimension is related to cognitive function and it might be expected that this score would correlate with this change in reaction time. However, none of these correlations could be confirmed with the Spearman calculations and it would be beneficial to repeat this study with larger groups.

Our detected change in reaction time might be expected given that typical symptoms associated with cybersickness, such as disorientation, might be expected to impair cognitive function. However, early attempts at measuring changes in cognitive function using a grammatical reasoning task found no effect related to simulator sickness [46]. It has also been reported that simulator sickness, while impacting on the motivation of participants, does not impact cognitive function [48]. It may be that we detected this change in reaction time because of the simple nature of the single choice task, and because it was administered immediately after the termination of virtual exposure. It was also a very rapid and simple test, only taking on the order of five minutes to administer.

We also note that these significant correlations between reaction time and our nausea measures were found in the pooled results (see Table 4). When the conditions were considered separately, the Parrot coaster (see Table 2) indicated significant correlations but the Helix coaster (See Table 3) did not. There is one data point in the Parrot condition where a high reaction time difference was found (see Figure 2) and although there was no reason to exclude this measure from the analysis it may have influenced the correlation. Regardless, given the potential use of this technology for training, the indications from this study are that further objective measures of cognitive function should be included in studies of cybersickness. These results also suggest that research to better quantify the duration of the effects of cybersickness on cognitive function would be of value.

Scores from MSAQ were previously found to correlate with both the Pensacola Diagnostic Index [28] and the Nausea Index [24]. Unlike our simple nausea measures, the MSAQ questionnaire is too complex to use for continuous monitoring of the participant's condition. Therefore, the next issue we addressed in this study was how well our nausea measures (standard nausea score and voluntary exposure time) correlated with the traditional MSAQ measures [20]. Our two simple nausea measures were significantly correlated with each other, and also with the MSAQ-Total and all of the MSAQ subscales except the MSAQ-Peripheral. These correlations were confirmed using both parametric and non-parametric approaches, and provide validation for their use in further cybersickness studies.

Our standard nausea score was intended to provide an average measure of the severity of nausea over the full 14 minutes of the virtual experience participants. Apart from the correlations with the MSAQ measures, it was also found to be was correlated with the measured change in reaction time. The strong correlation with the MSAQ-Gastrointestinal subscale was of particular interest given that this subscale is also designed to measure symptoms related to nausea. The three subscales are not orthogonal to one another [20], however, given the correlation with the MSAQ-Central score, it is also possible that the participant's nausea impacted on their capacity to use the reaction time measurement approach, rather than directly reflecting a reduction of cognitive function.

In terms of our two nausea measures, voluntary ride duration suggests itself as the most objective measure of participant nausea. However, only 10 of the participants stopped the experience early, perhaps reducing the sensitivity of the scale. Furthermore, sensations of cybersickness can be influenced by the level of control the user has [45] and some participants may have continued to the end simply given the awareness that the ride would cease after 14 minutes. In future studies, it may be desirable to provide longer experience times and not disclose the exposure time to participants. The standard nausea measure combined both the subjective rating, and the way it developed over time. This average rating was more subjective and dependent on the participant's interpretation of the scale.

For the 10 participants who finished early, we assumed the participant's nausea would not increase. We expect that this might underestimate their overall nausea sensation as it is probable that their nausea rating would have increased if they had not made a decision to stop the experience.

The final issue we considered was how well the MSSQ score [18], correlated with our simple nausea measures, and the changes in participant reaction time. The MSSQ is a revised form of Reason and Brands Motion Sickness Susceptibility Questionnaire [26]. The revised MSSQ has been validated in a number of studies and used for a number of years in the study of motion sickness. While the instrument is good at predicting who will be motion sensitive, it is known to be much less effective at predicting individuals who are resistant to motion sickness [18]. Correlations between laboratory measures of motion sickness and the Motion Sickness Susceptibility Questionnaire (MSSQ) [18] are often observed to be low, and one reason for this is the differences in the provocative nature of different stimuli [47]. There is also some uncertainty in questionnaire responses, as individuals often have different histories of the motion exposure being surveyed. Some of the modes of transport are not necessarily experienced in all regions. For example, frequent ferry and boat travel, and even long bus trips, are unusual in some regions.

Most of the correlations between the MSSQ and our other measures were not significant. However, using non-parametric approaches, we found significant correlation between the MSSQ and the MSAQ-Total, MSAQ-Gastrointestinal and MSAQ-Central measures. The MSSQ has an estimated validity at around $r = 0.45$ for predicting motion sickness [18]. Our three correlation values (0.49, 0.45, 0.44) were consistent with these previous results where significant correlations were found (0.42, 0.44, 0.51, 0.45, 0.49) [18].

The two roller coaster experiences used in the study provoked different levels of nausea in participants. This difference was in terms of both the severity and speed at which participants developed nausea. It is therefore interesting to reflect on the design variations between the roller coasters and the possible cause of these differences. Subjectively, the Helix roller coaster contains a much greater level of detail and realism than the more abstracted ParrotCoaster. Fidelity or graphic realism has previous been highlighted as a factor that can increase simulator sickness [43]. In flight simulators, flying close to the ground also causes higher incidence of simulator sickness than flying at higher altitudes [48]. This is usually explained in terms of increased visual flow, due to fast changing detail experienced when flying at lower heights above terrain. The level of detail, the placement of scenery in the Helix coaster, the track configuration, as well as the higher velocity of this ride when compared to the Parrot coaster, suggests a similar cause; that is higher levels of visual flow may be responsible for the increased nausea.

More objective characterization of the optical flow characteristics of the two scenes, such as visual complexity, speed, amplitude and frequency of visual stimuli [49, 50] are required to allow these results to be generalized, and this is the subject of further work. This more objective description of the experience is important to allow for better comparison of results from cybersickness studies. However, many of these visual stimuli calculations require tracking the scene camera positions (x, y, z roll, pitch, yaw) over time. One limitation of our study is that the two virtual experiences were provided by third parties and therefore information about camera positions were not available for analysis. Ideally in future work we would develop our own software to allow for these camera positions to be recorded, along with participant head movements.

5 Conclusion

Simulator sickness, cybersickness, and related conditions such as motion sickness and space sickness, have been studied for a long time. These conditions are complex, being associated with a range of situational factors that impact on individuals in different ways. Both subjective and objective approaches have been applied to try and understand the factors that impact on such conditions, as well as the susceptibility of individuals to the various symptoms. As these types of environments are being more generally adopted for training purposes, we were particularly interested in studying changes in cognitive function in relation to cybersickness, and also understanding the onset of nausea on a provocative virtual experience.

We used a simple measure of cognitive function, namely a reaction time test that could be administered immediately following the virtual exposure. We measured significant changes in reaction time due to cybersickness. It is not clear how long this reduced cognitive function lasts, and further work will need to be carried out to determine how long it persists. These changes in reaction time were correlated with our standard nausea score, and we also found a parametric correlation between this reduced reaction time and a number of the MSAQ measures. However, we could not confirm any of these correlations using non-parametric tests. Ideally we would expect the MSAQ-Central to correlate with such an objective measure of changed reaction time and further work with larger sample sizes is required.

To avoid too great an impact on the immersion of the virtual experience, we used simple nausea measures that only required minimal feedback from participants. These nausea measures were the duration of voluntary exposure, and a standard measure of nausea ratings over the experience period. Both measures were significantly correlated with more traditional simulator sickness instruments, namely Golding's revised Motion Sickness Susceptibility Questionnaire (MSSQ) [18] and the Motion Sickness Assessment Questionnaire (MSAQ) [20]. Both the voluntary duration and standard nausea score were also strongly correlated with the MSAQ-Gastrointestinal subscale that is intended to measure such nausea effects.

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